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Recent developments in noise research at Deutsche Bahn (noise assessment, noise source localization and specially monitored track)

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Abstract

To strengthen the environmental friendliness of railway traffic in Germany, Deutsche Bahn (DB) is in the process of performing a major research programme concerning noise reduction. To realize this, the DB 'Low Noise Railway' programme deals simultaneously with the noise treatment of trains and the wheel/rail system as well as other topics.

The assessment of a particular sound experience as annoying *noise* is a very personal judgement and cannot be dealt with by physical quantities alone. To permit a better understanding of this phenomenon and to support the legislative authorities, the assessment of noise *quality* is being investigated in detail.

To reduce railway noise, the exact location and the magnitude of the different sound sources have to be known. This can be analyzed with an array of many microphones which has been developed by DB in the last few years.

Most recently, DB has developed the acoustic concept of the 'Specially Monitored Track (SMT)' into a practical application and is now starting to upgrade SMT to increased performance and at a lower cost.

1. Introduction

In the last few decades, mobility in Europe, based on automobiles for individual traffic and lorries for freight traffic, has increased more and more; yearly growth rates of more than 10% have often been reported by statistics. These growth rates, compounded over the years, cannot easily be handled in an environment-friendly way. The European Commission has therefore given clear political signals to get more passengers and more freight to use the railways. An efficient

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trans-European transportation network is indispensable to handle this increased mobility. To strengthen the environmental friendliness of railway traffic in Germany [1], Deutsche Bahn (DB) is currently carrying out major noise reduction research programme [2].

The assessment of a particular sound experience as an annoying *noise* is a very personal judgement and cannot be dealt with by physical quantities alone. Therefore, the question of when *sound* is qualified as *noise* is a very basic one and is investigated in parallel with the above-mentioned activities taking both physiological and psychological aspects into account.

In several European countries there is a 'bonus' approach for railway-generated noise taking into consideration the fact that, for a given sound pressure level, railway noise is to some extent less annoying than noise created by individual car and lorry traffic because of the dissimilar acoustic characteristics. In Germany this bonus is taken to be $-5\,\mathrm{dB(A)}$; in other European countries, a corresponding bonus exists. To improve the understanding of this phenomenon and to support the legislative authorities in finding suitable limit values, the assessment of noise *quality* is being investigated in detail. The investigations are focussed on the noise effect of high-speed trains and of conventional passenger and freight trains. Additionally, studies concerning the awakening of sleeping residents and the acoustic annoyance in rooms facing the traffic are in progress.

To comply with the ambitious legislative limit values for noise perception in Germany, which are shown in Table 1 [3], the production, transmission and perception of sound have to be investigated simultaneously. Knowledge of the strength of the different noise sources in the wheel/rail system is vital. Only with this understanding of the overall noise-production process will a good cost-to-benefit ratio in noise-reduction research be achieved. In keeping with this reasoning, DB has developed in the last few years a microphone-array for the localization and visualization of noise sources. This technique enables sound sources located close to each other to be separated measurements and it supports the validation of computational calculations of sound emission.

To reduce the noise generation from rail surface corrugations, DB has, in the last few years, introduced the acoustical concept of the "Specially Monitored Track (SMT)" ('Besonders überwachtes Gleis (BÜG)') and brought it to practical application. The SMT concept is based on the periodic acoustic monitoring of the selected track section by means of a test coach equipped with special sound measuring technology. If the noise is above a certain limit, grinding the track section will remove the minute periodic rail surface irregularities which excite the train wheels and lead to sound radiation from the wheels and the rail itself. The German Federal Railway Authority (EBA) officially confirmed SMT as a noise-reduction system with an effectiveness of $-3\,\mathrm{dB(A)}$ for ballasted and slab tracks.

Table 1
Legislative noise limits in Germany in dB(A) [3]

Limit values of the averaged sound pressure level SPL in dB(A)	Daytime (06 a.m.–10 p.m.)	Night (10 p.m.–06 a.m.)
Near hospitals, schools, old people's home	57	47
In residential areas	59	49
In mixed residential/industrial areas	64	54
In industrial areas	69	59

2. Sound perception and noise assessment

In several European countries, there is a 'bonus' approach towards railway-created noise (corrective factor rail/road traffic noise). This is based on consideration of the fact that, for a given hourly average sound pressure level, railway noise is to some extent less annoying than noise created by private car and lorry traffic because of the dissimilar acoustic characteristics (Fig. 1).

The basic investigations were performed in the 1980s [4], leading Germany in 1990 to adopt the permitted "rail bonus" of -5 dB(A) [3]. The same holds for Austria, while, for example, in France it is -3 dB(A), in the Netherlands it is -7 dB(A) and in Switzerland it is -5 dB(A) to -15 dB(A) depending on the intensity of the rail traffic.

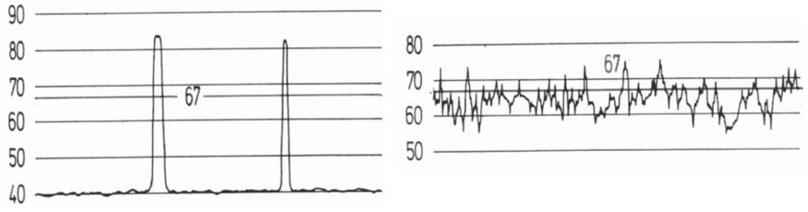
In the meantime, the railway traffic situation in Germany has changed significantly as high-speed trains have come into operation; existing lines have been upgraded for operations up to 200 km/h and the mix of passenger and freight traffic has shifted. To reflect these changes and to support the legislative authorities, the assessment of noise quality is being re-investigated in detail. The focus is on the comparison of rail and road noise, the perception of high-speed train noise and the annoyance caused by conventional passenger and freight train noise. Also the change in the degree of annoyance near newly built and upgraded railway lines have been considered.

The investigations already finalized clearly show (see e.g., Refs. [5–8]) that the rail bonus is still a valid approach for the annoyance disparity between railway and road traffic and that -5 dB(A) is the minimum bonus over the whole day (Fig. 2). A novel outcome has been the variation in the annoyance disparity during the day; in the night-time the bonus could be even much higher. Furthermore, high-speed traffic is no more annoying to the residents than standard passenger trains.

2.1. Comparative study of the noise generated by road and rail traffic

Overall, the differences in the nuisance caused by rail and road traffic noise determined in the earlier studies were confirmed. Very much as in the "IF Study" [4], the recent study [7] concludes that rail traffic noise only causes the same nuisance as road traffic noise given equivalent continuous noise levels (total exposure over a 24-h period) of some 4 dB(A) higher (Fig. 2).

For answers given by respondents with regard to disrupted sleep and nuisance levels at night, there was actually a mean difference in favour of rail traffic noise of approximately 10 dB(A). This



Railway traffic, SPL mean value 67 dB(A)

Road traffic, SPL mean value 67 dB(A)

Fig. 1. Characteristics of noise creation by railway traffic compared to road traffic with identical mean value of the sound pressure level (SPL).

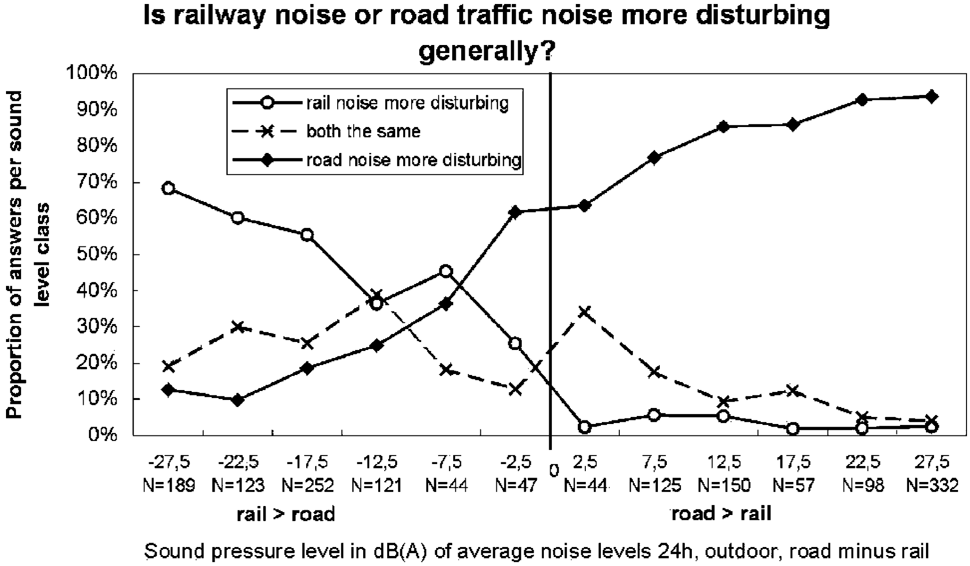


Fig. 2. Result of the noise assessment studies illustrating less annoyance to residents by rail traffic compared to road traffic.

value also confirms the earlier findings of the IF Study. The 5 dB(A) 'nuisance differential' in rail's favour set out in 16. BImSchV is a politically determined figure and was opted for on account of the high night-time nuisance differential and the corresponding daytime value.

Additionally it has been confirmed through this study that, given exposure to comparable noise levels, roadside residents are considerably more likely to keep their windows closed than line-side residents, which similarly indicates that rail traffic noise causes less nuisance.

2.2. Study of the nuisance caused by high-speed trains citing the Hannover-to-Göttingen new-built/upgrade line

The introduction of new high-speed ICE trains in Germany led to fears amongst large numbers of affected line-side residents that noise levels would rise. Many living in the vicinity of planned new lines were deeply concerned and afraid the trains would create unacceptable noise. The high running speeds of ICE trains, for instance, lead to correspondingly steep rises in noise when the trains pass buildings near the track. It was also feared that the aero-acoustic noises generated by these trains and the very specific type of sound that emanates from their pantographs might be detrimental and be viewed critically by those affected. Given this situation, the applicability of the rail bonus to high-speed traffic is being called into question. The study thus aimed to gain insights into possible additional impairments suffered by affected line-side residents due to features specific to modern high-speed rail traffic.

Comparing average responses to rail noise with those relating solely to ICE traffic, it is revealed that, given the same incidence of noise, the noise nuisance arising from ICE services is in no way greater than that arising from conventional rail traffic. It can be deduced from the results that where the typical exposure levels considered for the purposes of this study are concerned, high-speed traffic as a whole does not give rise to higher levels of noise nuisance and discomfort for line-side residents than is the case with conventional train operations.

2.3. *Study of the nuisance caused by passenger and freight trains on DB tracks*

This study revealed that the road-rail nuisance differential is particularly favourable to the rail mode at night. There are usually more freight than passenger trains running on the DB network in the night-time period. This was clearly at odds with general technical insights hitherto that had led to freight trains being given an inferior classification compared to passenger trains on account of their characteristic noise profile. DB accordingly arranged for studies to be conducted in respect of lines with either a high or a low share of freight traffic. The aim behind these studies was to elicit the degree to which line-side residents are disturbed by freight/passenger trains.

The findings showed overall that, given the same exposure to noise, the share of line-side residents who feel disturbed by freight trains is only slightly higher than the share of line-side residents who feel disturbed by passenger trains. Indeed, where disruptions to sleep in the night-time period are concerned, there are no notable differences in respondents' answers between the nuisance curves for passenger and freight trains. This agrees with the study described in Section 2.1, which revealed that the road/rail nuisance differential at night is significantly greater than during the day.

3. Noise source localization

In railway noise research, it is critical to identify the individual contributions of the different sound sources to the overall noise level. Both the exact location and the magnitude of the source are of interest. This cannot be performed by measurements with a single and omni-directional microphone as a single microphone is not able to distinguish between the different sources. Instead, an arrangement of many microphones has to be used for these purposes. To give accurate results, the microphone grouping and the related signal processing have to match and therefore have to be examined in detail prior to service.

During the development of this microphone array, based on the Brüel & Kjaer spatial transformation of sound fields (STSF) hardware, four different distribution patterns were evaluated in detail [9]. The spiral array with irregularly distributed microphones showed the best results regarding incorrect localization of sound sources due to side-lobes and signal-to-noise ratio. The commonly used X-configuration as well as the circle and grid pattern showed distinct drawbacks caused by side-lobes in comparison to the spiral array. By adjusting the measurement distance or the size of the spiral, it is possible to adjust the array to other frequency ranges. Shorter distances lead to a useful range at lower frequencies while for longer distances the useful range shifts to higher frequencies.

DB's microphone array in a spiral arrangement with either a 4 m diameter or a 2 m diameter can be equipped with up to 90 microphones. The array characteristics, resolution and signal-to-noise ratio were evaluated by numerical simulations [9]. The spiral configuration with irregular distributed microphones on a 4 m diameter with typically 0.4 m microphone spacing leads to a useful frequency bandwidth from 200 Hz to 3.4 kHz at 7.5 m measuring distance; this is very sufficient for most applications (Fig. 3).

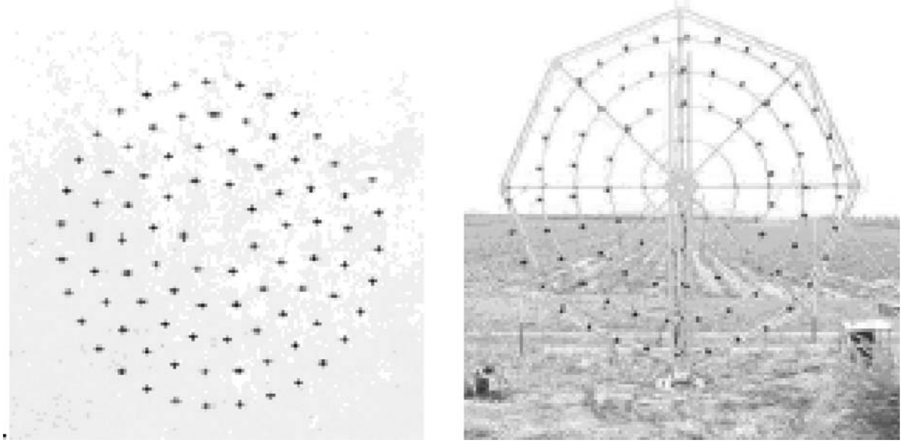


Fig. 3. Spiral microphone-array with 4 m diameter.

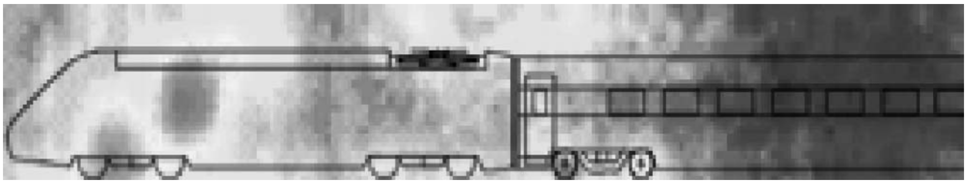


Fig. 4. Noise source localization by microphone-array measurements.

Measurements with this array were used to investigate wheel and rail noise from a high-speed train. With this array, DB is now able to localize and quantify the dominant noise sources in the relevant frequency bands [10–13]. An example is shown in Fig. 4.

4. The acoustically Specially Monitored Track

In the last few years, DB has implemented the acoustic concept of the 'Specially Monitored Track (SMT)'. The SMT concept is based on the periodic acoustic monitoring of the relevant track section by means of a test coach specialized for sound measuring. Should noise exceed a certain limit, grinding the track section will remove the minute periodic rail corrugations which excite the train wheels and lead to sound radiation from the wheels and the rail itself. Fig. 5 shows a representative example of the sound pressure level before and after grinding the rails.

The Federal Railway Office (EBA) officially confirmed SMT in 1998 as a noise-reduction system with an effectiveness of $-3\,\mathrm{dB(A)}$ for ballasted and slab tracks. It should be noted that SMT is used mostly on track sections on which freight wagons with cast-iron brake block are most common. For composite brake blocks, which lead to smooth wagon wheels with much less noise emission, and for disc-braked vehicles, the noise reduction by the SMT is twice the stated value.

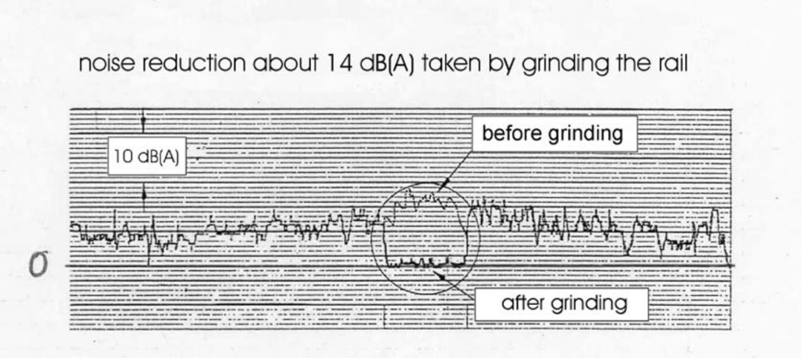


Fig. 5. Noise emission from railway line before and after local grinding.

The experience of the last few years has now shown that the compatibility conditions for the use of the SMT stated by the authority, i.e.,

- periodic acoustic monitoring of the relevant track section by means of a test coach specialized in sound measuring;
- monitoring of the grinding quality of the track section that has been ground;
- application of the different grinding procedures;

require further development and will have to be adjusted according to technological progress. Furthermore, extensive investigations are essential to improve the basic understanding of the relationship between the track surface condition and the sound emission of the railway vehicles.

4.1. Periodic acoustic monitoring

The quality of the periodic acoustic monitoring of the relevant track section by means of a test coach specially adapted for sound measuring is one of the crucial factors affecting the success and reputation of SMT as a local countermeasure against the noise emission of a railway line. In Germany, the federal authorities have stipulated that the acoustic monitoring has to be performed at least every 6 months and that the quality and the process of the grinding work has to be supervised and authenticated. For these purposes, a reliable measuring system is needed for use soon after grinding the track section. In addition, the company actually performing the track grinding is given a clear quality target, which has to be met. Only by failing to meet the target can the grinding work be assigned to different competitors when their work quality will be recorded.

Together with industrial partners, DB has developed measuring devices for rail surface corrugations both to investigate the growth process, see e.g., [13], and to perform in-situ quality control directly after grinding (Fig. 6). The relevant features are listed in Table 2.

The SMT Quality Control Device is adapted to DB's special sound measurement test coach as well as to sound measurements near the track so that a suitable limit curve for an optimum acoustically ground rail can be specified. First actions in this direction supported the basic concept and, with appropriate software, the limit curve and conformance to the limit can be recorded for the benefit of all the relevant partners in the SMT process.

Fig. 6. Rail with surface corrugations (left), ground rail (mid) and measuring device for specially monitored track, SMT (right).

Table 2
Relevant features of DB's devices to measure rail surface corrugations

DB's devices to measure rail surface corrugations	RM 1200 E	SMT quality control device
Main task	Research on growth of corrugations	Check of rail surface quality directly after grinding process
Measuring principle	Mechanical sensor	Mechanical sensor
Simultaneous two-rail operation	No	Yes
Processed wavelength range (cm)	1–10	1–10
Roughness amplitude resolution (μm)	2	10
Scanning rate along rail (mm)	2	2
Measuring velocity (m/s)	0.05	Approx. 1.5, walking speed

During the test run on a specific track section, the sound measuring coach records various data such as the measured sound pressure level, the coach velocity and the location. Until recently, it has been sufficient for only a reduced set of this information be stored for later examination. In future, a database for a more sophisticated analysis of the whole SMT process will be continuously filled with all relevant data. This enables

- comparison with former measurements;
- early derivation of trends within an individual track section such as disparity in the surface quality giving an indication that the limit curve will be exceeded in the future;
- development of the acoustic quality of both individual track sections and the whole length of the SMT in service;
- quality monitoring of the rail surface condition after grinding.

Relevant data for analysis are the type of track construction, curvature and cant, track irregularities, inspection schedule of grinding and maintenance. This overview of the full set of significant parameters will be used later for improving the effectiveness of the SMT process and to achieve a higher noise reduction rate.

4.2. Optimization of "acoustic grinding"

The financial and operational expenses of DB for acoustic grinding are more than counterbalanced by the reduction of expenses for noise barriers or noise protection windows. From time to time, this trade-off has to be performed again as the cost structure of the SMT is not static and an improvement of the SMT performance permanently supports the former decision favouring the SMT. DB's research is therefore progressing in two directions simultaneously: to reduce the costs for this particular reduction rate and to increase the noise reduction rate for the current cost structure.

The typical noise reduction curve over time of the current SMT in Germany is shown in Fig. 7. If a certain track section is subject to SMT, grinding will immediately decrease the rail noise to well below 48 dB(A). Approximately half a year later, the noise emitted by the track section will be 2 dB(A) lower. Later, the noise emission will increase with time and, after around 2 years, the threshold value of 51 dB(A) will be reached. This value is the so-called 'base value' in the German legislative framework SCHALL 03 [3], valid for ballasted tracks with wooden sleepers. Reaching this threshold value initiates the next rail grinding process. In current practice, the noise emission fluctuates over time around the mean value of 48 dB(A) with an amplitude of 3 dB(A).

The idea behind the low-cost option is to follow the base value by increasing the frequency of the grinding but with a lower amplitude. Current research is now looking for the cost-optimized frequency–amplitude pairing. The high-performance option works with an even higher frequency and smaller amplitude in comparison to the low-cost option, but the striking feature is the lower base value. This option aims for a noise reduction rate of effectively −5 dB(A).

In both options, the amplitude is reduced and the required grinding depth for each cycle can be lower so that the grinding train can travel at a higher working velocity over time. Above a certain

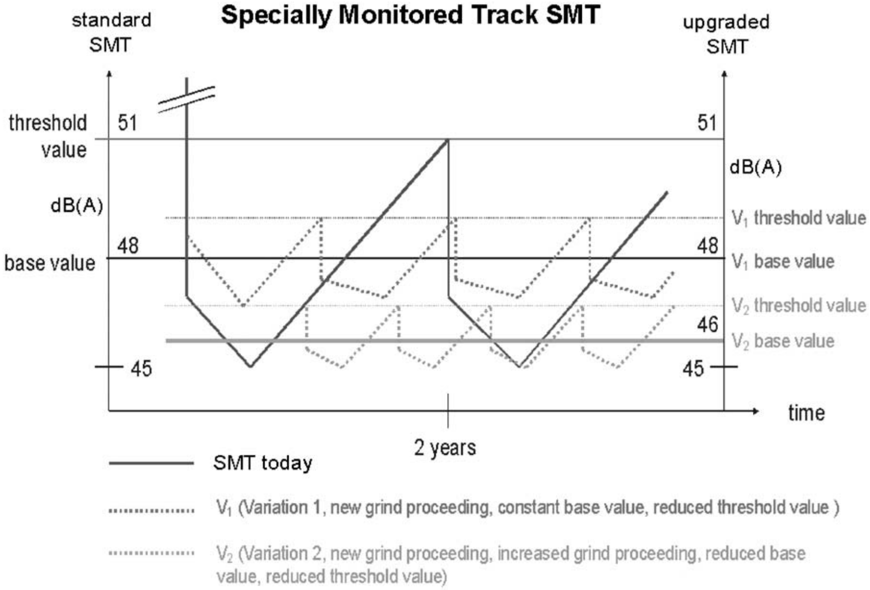


Fig. 7. Noise reduction grinding as a function of time of the SMT technique using track grinding.

travelling speed, no possession of the specific track section is necessary and the grinding train can be synchronized with the regular train-free intervals on the track section. This leads to a high economic benefit as the operational effort can be drastically reduced.

Further development of SMT and related techniques is towards a mobile measuring device for rail surface roughness to perform in-situ quality control directly after grinding, and towards an application of SMT to slab track equipped with a sound-absorbing layer.

5. Conclusions

DB is undertaking a major noise-reduction research programme to respond to public demand for low-noise railway traffic in future. All aspects of the creation, the transmission and the perception of noise are being tackled in several projects by various workgroups launched by DB experts along with acoustic professionals from other European railway undertakings and external institutions.

One important result is that the current studies of railway noise assessment by line-side residents again support the 'bonus' approach stipulated by the legislative authorities. Furthermore, the noise source detection by microphone arrays and the SMT technique are now in service at DB.

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